Future Generation Computer Systems 41 (2014) 44–52

Contents lists available at ScienceDirect

Future Generation Computer Systems

journal homepage: www.elsevier.com/locate/fgcs

A game-theoretic approach to the financial benefits of infrastructure-as-a-service

Jörn Künsemöller *, Holger Karl

University of Paderborn, Computer Networks Group, EIM-I, Warburger Str. 100, 33098 Paderborn, Germany

HIGHLIGHTS

- We propose a game theoretic-model of the infrastructure-as-a-service market.
- We examine pricing and usage dynamics and how they depend on factors like economies of scale and load distribution.
- The possibility of hybrid clouds is essential for the client to profit of a purely on-demand cloud.
- A reserved instance option causes higher on-demand instance prices and costs to the client.

ARTICLE INFO

Article history:
Received 30 June 2012
Received in revised form
9 March 2014
Accepted 16 March 2014
Available online 29 March 2014

Keywords:
Cloud computing
Markets
Game theory
Pricing
Infrastructure

ABSTRACT

Financial benefits are an important factor when cloud infrastructure is considered to meet processing demand. The dynamics of on-demand pricing and service usage are investigated in a two-stage game model for a monopoly *Infrastructure-as-a-Service (IaaS)* market. The possibility of hybrid clouds (public clouds plus own infrastructure) turns out to be essential in order that not only the provider but also the clients have significant benefits from on-demand services. Even if the client meets all demand in the public cloud, the threat of building a hybrid cloud keeps the instance price low. This is not the case when reserved instances are offered as well. Parameters like load profiles and economies of scale have a huge effect on likely future pricing and on a cost-optimal split-up of client demand between either a client's own data center and a public cloud service or between reserved and on-demand cloud instances.

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1. Introduction

When a client considers cloud computing, a variety of factors like privacy concerns and strategic decisions have to be reckoned with the particular case. In particular, costs are a key factor in the decision process. Case studies that ask whether or not processing in the cloud is feasible usually only regard current prices for cloud services. Since the cloud market develops, assuming constant prices is insufficient for long-term decisions. This paper abstracts from current market prices and investigates the interaction of cloud provider and clients from an analytical perspective. A general understanding of how providers and clients potentially benefit financially from *Infrastructure-as-a-Service (IaaS)* can help clients to appraise price uncertainty in strategic resource planning decisions. Providers gain insights on how pricing and charging models affect service usage.

Our analysis focuses especially on the combined use of cloud services and an own data center, which offers a variety of possibilities how clients may split up their processing demand. While cloud service prices are most likely considered in the resource allocation decision of a client, it is unknown how this interrelation affects future cloud pricing.

Market dynamics depend on provider and client behavior. By contrasting the possible actions of these market actors, game theory can identify stable market situations that suggest likely or advisable behavior. We contribute a game-theoretic model and determine its equilibria in order to estimate future pricing and expected usage of IaaS in hybrid cloud scenarios. We further discuss the impact of factors like load distribution and economies of scale on the model. Also, the effects of a simultaneous offer of reserved instances is explored.

This paper is organized as follows. The contribution of this paper is put into relation to other research in Section 2. A market model for on-demand cloud infrastructure is developed throughout Section 3. In Section 4, the model is applied to an example case. Section 5 discusses the impact of a reserved charging option on the market. A general discussion of research results is presented in Section 6, which also concludes the paper.

* Corresponding author.
E-mail addresses: jkuensem@mail.uni-paderborn.de (J. Künsemöller), hkarl@mail.uni-paderborn.de (H. Karl).

http://dx.doi.org/10.1016/j.future.2014.03.005
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2. Related work

Several publications deal with the suitability of cloud services as a substitute for on-site corporate IT. Guidelines for the decision process like [1,2] usually include a financial comparison of feasible solutions. Calculation models for *total cost of ownership (TCO)* of a data center [3,4] can be taken as a basis for this. There are also ready-to-use calculators [5] for a direct comparison of expected costs based on specified demand. A cost model specifically for hybrid clouds is provided by [6]. Contrary to such case-based comparisons from a client's point of view, our approach allows to draw general conclusions on pricing and usage dynamics from a market model that considers the provider's perspective as well.

There also is game-theoretic research on cloud computing. Many publications focus on algorithmic solutions in resource management, e.g. [7,8]. Several recent papers also discuss cloud instance pricing, though. For markets where providers compete in quality of service and price, the existence of a Nash equilibrium solution has been shown for a duopoly [9] and for n competitors [10]. In [11], an evolutionary approach is used to determine stable pricing. The authors in [12] study how the competition amongst clients for resources affects pricing. Instead of exploring instance price in a competitive environment, our work examines price and service utilization in hybrid clouds when the provider is in a monopoly position.

The negotiation of cloud instance pricing is approached by [13] in a 'one provider — one customer' bargaining problem. Our paper contributes a model where one provider serves many customers and the price is not bargained but fixed. Whether a provider should better provide instances on demand and at a fixed price or offer them in a spot market is discussed in [14]; a combined approach is also explored. [15] explores the distribution of resources on reserved, on-demand and spot market instances that maximizes provider revenue. We contribute similar research by investigating whether a provider should offer reserved instances, on-demand instances or both and what prices for the different instance types maximize provider profit.

The proposed market model has been previously published as work-in-progress [16]. This paper contributes a revised and improved presentation as well as additional research concerning reserved instances.

3. A game-theoretic market model for infrastructure-as-a-service

3.1. Setup

A game-theoretic model of an on-demand infrastructure cloud market is suggested in the following; the goal is to estimate future pricing. The model is set up as one player being a provider that offers an on-demand computation instance. Such an instance provides capacity for processing and storage like a physical server and fees apply only when the instance is in use. The other player is a client that may utilizes the offered product. An *extensive form game* [17] is used since the provider makes an offer and subsequently the client is free to accept it or not. Fig. 1 shows the proposed game model. The provider chooses a price and subsequently the client is free to use the service at these terms at any amount in combination with an own infrastructure in order to meet its processing demand.

We assume that the provider tries to maximize profit and the client tries to minimize expenses. Hence, utilities are based on client costs and provider profit. How the model can be solved based on these utilities is discussed in the following.

At a constant utilization of the cloud service, there is an incentive to raise the instance price as this increases the profit of

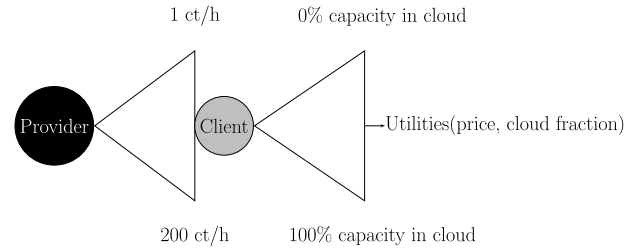

Fig. 1. A market model for IaaS using continuous strategies.

the provider. This incentive is not given when a further price raise would result in lower profit. This can be the case, for example, when the client stops using the cloud. The client may follow the strategy to use the cloud when the price is lower than some $p_{\text{threshold}}$ and to build a data center when the price is higher than $p_{\text{threshold}}$. This client's strategy is in a Nash equilibrium [18] with the provider's choice of a price that is just below $p_{\text{threshold}}$. A Nash equilibrium is a strategy combination where no player has an incentive to unilaterally change its strategy. Thus, they are usually regarded as stable market states. Such an equilibrium exists for any threshold price $p_{\text{threshold}}$ amongst many others.

The client will accede to the agreement, though, whenever a price is offered that actually causes lower costs in the cloud. As a consequence, any equilibrium where the client has an incentive to change its strategy during the game can be considered a non-credible threat. For example, suppose a specific cloud service price at which the cloud solution is a lot cheaper than an own data center to the client but the provider still makes positive profit. Further, the client follows the strategy to use the cloud service up to this price and to use an own data center if the cloud service is more expensive. Then this client's strategy is in equilibrium with the provider's strategy to offer exactly this price. Nevertheless, once the provider actually offers a higher price, the client might still benefit from the cloud service and prefer it over the data center option. Since the client will then change its strategy accordingly, the original equilibrium strategy is non-credible. As a consequence, unilateral change (changing the price) is safe for the provider when the client subsequently changes its strategy as well. Non-credible equilibria can thus be safely ignored. They can be sorted out by asking for *subgame perfection* [19] which means that strategies in equilibrium have to remain best responses throughout all possible in-game situations.

Clients are expected to choose different amounts of cloud instances based on the provider's offer. What fraction of a client's demand is met in the cloud depends on what combination of cloud and own infrastructure causes the lowest costs to the client at a given price. The price that offers the highest profit to the provider is in a subgame-perfect Nash equilibrium with the cloud fraction that belongs to the cheapest solution to the client at any given price.

Throughout the following sections, the utility functions of the game model are developed. Section 3.7 presents the final utilities and a calculation of the equilibrium solution.

3.2. A simple cost model

Several calculation models for comparing the cost structure of cloud services and local data centers exist [5,3,4]. The cost models underlying these case studies can be easily generalized into two linear relationships.

Let us consider data center costs as the product of a number of servers n that is necessary to meet the maximum demand of a client and a constant c that includes all annual amortization and operation costs for one server (Eq. (1)).

$$\text{DC}_{\text{costs}}(c, n) = c \cdot n \tag{1}$$

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